

A DESI DR1 Radial-Velocity Search for Dark Compact Companions: A Strong but Unconfirmed Candidate Around a dM0 Star

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4 ABSTRACT

5 We present a conservative, fully reproducible search for radial-velocity (RV) variability in the public
6 Dark Energy Spectroscopic Instrument (DESI) Data Release 1 (DR1) Milky Way Survey. Using only
7 per-epoch RV measurements, we identify stars whose velocity variability is both highly significant
8 and robust under leave-one-out tests. A “negative space” validation pipeline then rejects ordinary
9 luminous companions using Gaia DR3 astrometry, WISE infrared photometry, GALEX ultraviolet
10 imaging, TESS and ZTF time-domain photometry, deep Legacy Survey imaging, and archival X-ray
11 and radio catalogs.

12 One system, Gaia DR3 3802130935635096832 (DESI TargetID 39627745210139276), emerges as the
13 most extreme survivor. DESI provides four RV epochs spanning 38.9 days with a maximum catalog
14 RV span $\Delta RV_{\max} \approx 146 \text{ km s}^{-1}$. A constant-RV model is rejected at $\Delta\chi^2 \approx 2.7 \times 10^4$ (DESI-only),
15 and the variability remains highly significant under leave-one-out tests.

16 A key forensic update is that Gaia DR3 resolves a neighbor at $\rho \simeq 0.69''$ with $\Delta G \simeq 2.21$ mag,
17 implying a G -band flux ratio $b_G \simeq 0.13$ and requiring blend-aware validation. We perform blend-
18 aware remeasurement of the DESI spectra using PHOENIX templates and physically motivated flux-
19 ratio priors; the large RV swing persists across these remeasurements. We then resolve the origin
20 of previously observed arm-split pathologies by downloading per-exposure, per-camera DESI spectra
21 (cframe products) and remeasuring RVs by wavelength region. Same-night exposures reveal that the
22 full Z -arm RV is unstable when sky-dominated wavelengths (9000–9800 Å) are included, while the Ca II
23 triplet window (8500–9000 Å) yields stable and repeatable RV behavior. Using only this empirically
24 “trusted” window, we recover a large RV swing $\Delta RV \approx 151 \text{ km s}^{-1}$ (from -85.6 to $+65.6 \text{ km s}^{-1}$),
25 and we find that the DESI catalog RVs for the same-night pair are biased low by $\sim 25 \text{ km s}^{-1}$ relative
26 to the trusted-window RVs, consistent with sky-region instability affecting the catalog solution.

27 Finally, we verify Gaia astrometric quality metrics via a direct query to `gaiadr3.gaia_source`
28 (script: `scripts/verify_gaia_metrics.py`), finding RUWE = 1.954 and astrometric excess noise
29 $\epsilon_{\text{AEN}} = 0.90$ mas (16.5σ significant) at $G = 17.273$. These values indicate a poor single-source as-
30 trometric fit consistent with unresolved astrometric complexity (orbital motion and/or duplicity), but
31 are not uniquely diagnostic given the resolved neighbor. We classify Gaia DR3 3802130935635096832
32 as a *strong but unconfirmed* dark compact companion candidate: the RV swing persists under con-
33 servative, windowed, per-exposure analysis, but a definitive dynamical mass claim requires follow-up
34 spectroscopy and/or high-angular-resolution imaging to separate the blended components.

35 **Keywords:** Radial velocity(1332) — Compact objects(288) — M dwarfs(982) — Spectroscopy(1558)

36 1. INTRODUCTION

37 Quiescent compact objects—white dwarfs (WDs),
38 neutron stars (NSs), and stellar-mass black holes

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39 (BHs)—are expected to be abundant in the Milky Way
40 but are difficult to detect when not accreting or other-
41 wise luminous. Radial velocities provide a purely grav-
42 itational discovery channel: a compact companion can
43 induce large reflex motion in an ordinary star while con-
44 tributing negligible light. Modern multi-epoch spectro-

scopic surveys are therefore natural hunting grounds for unseen companions.

DESI DR1 provides per-epoch RVs for millions of stars in the Milky Way Survey. While DESI was not designed as a time-domain survey, the combination of multi-epoch coverage, high spectral resolution, and uniform data processing enables a systematic search for RV outliers. In this work we:

1. define conservative RV-variability metrics that are robust to outliers;
2. scan the DESI DR1 Milky Way Survey for high-significance RV variables;
3. apply a multi-wavelength “negative space” filter that searches for *gravity without light*;
4. perform targeted orbital and forensic analyses of the strongest surviving candidate, including blend-aware remeasurement and per-exposure wavelength-region truth filtering.

All analysis scripts, configuration files, and machine-readable products are publicly available at <https://github.com/simulationstation/DESI-BH-CANDIDATE-SEARCH>.

2. DATA SETS

2.1. DESI DR1 Milky Way Survey

We use per-epoch DESI DR1 Milky Way Survey RVs from the `main-bright` and `main-dark` programs. For each epoch we extract:

- heliocentric radial velocity RV_i (km s^{-1});
- formal RV uncertainty $\sigma_{RV,i}$ (km s^{-1});
- modified Julian date t_i (days);
- DESI TARGETID;
- Gaia DR3 SOURCE_ID when available.

2.2. LAMOST archival spectroscopy

We identify two public LAMOST spectra (ObsIDs 437513049 and 870813030) of the target. These spectra robustly support an early-M dwarf classification for the dominant light source. However, independent RV measurement of these spectra is internally inconsistent across methods (FITS-header values vs CCF refits and wavelength-split CCF), so we treat LAMOST RVs as *non-decisive* for orbit fitting and retain LAMOST primarily as a spectral-type constraint.

2.3. Gaia DR3 astrometry and duplicity

We verify the key Gaia DR3 quality metrics via a direct `astroquery.gaia` query to `gaiadr3.gaia_source` (script: `scripts/verify_gaia_metrics.py`).

Table 1. Verified Gaia DR3 astrometric metrics for Gaia DR3 3802130935635096832.

Quantity	Value
Gaia G magnitude	17.273
Parallax ϖ (mas)	0.12 ± 0.16
RUWE	1.954
Astrometric excess noise ϵ_{AEN} (mas)	0.90
AEN significance ($\epsilon_{AEN}/\sigma_\epsilon$)	16.5

An elevated RUWE (commonly RUWE $\gtrsim 1.4$) indicates a poor fit of the 5-parameter single-source astrometric model and is often associated with unresolved binaries, blends, or other astrometric complexity. The parallax is poorly constrained and we therefore do not adopt a Gaia-only geometric distance.

A major forensic update is that Gaia DR3 resolves a close neighbor at a separation $\rho \simeq 0.688''$ with $\Delta G \simeq 2.21$ mag. This neighbor lies within the DESI 1.5'' fiber aperture and must be treated as a potential blend contaminant.

2.4. Additional surveys

The multi-wavelength validation uses WISE/2MASS photometry, GALEX NUV imaging, TESS full-frame-image photometry, ZTF multi-year g, r photometry, Legacy Survey imaging cutouts, ROSAT/XMM/Chandra X-ray catalogs, and NVSS/FIRST/VLASS radio surveys.

3. RV VARIABILITY METRICS

3.1. Single-target RV statistics

For each target with N RV epochs we define the maximum observed RV span:

$$\Delta RV_{\max} = \max_i (RV_i) - \min_i (RV_i). \quad (1)$$

To quantify the significance of variability we define:

$$S = \frac{\Delta RV_{\max}}{\sqrt{\sum_{i=1}^N \sigma_{RV,i}^2}}. \quad (2)$$

Table 2. Definitions for Equation (1).

Symbol	Meaning
RV_i	Radial velocity at epoch i (km s^{-1})
ΔRV_{\max}	Maximum RV span across all epochs (km s^{-1})
$\max_i(\cdot)$	Maximum over epochs indexed by i
$\min_i(\cdot)$	Minimum over epochs indexed by i
N	Number of RV epochs

Table 3. Definitions for Equation (2).

Symbol	Meaning
S	Global RV-variability significance (dimensionless)
ΔRV_{\max}	Maximum RV span (km s^{-1})
$\sigma_{\text{RV},i}$	RV uncertainty at epoch i (km s^{-1})
N	Number of RV epochs
i	Epoch index

3.2. Leave-one-out robustness and leverage

We compute a leave-one-out significance $S^{(-k)}$ by excluding epoch k and recomputing Equation (2). We then define:

$$S_{\min,\text{LOO}} = \min_{1 \leq k \leq N} S^{(-k)}, \quad S_{\text{robust}} = \min(S, S_{\min,\text{LOO}}). \quad (3)$$

We also define a leverage statistic:

$$d_i = \frac{|\text{RV}_i - \bar{\text{RV}}|}{\sigma_{\text{RV},i}}, \quad d_{\max} = \max_i d_i, \quad (4)$$

4. NEGATIVE-SPACE VALIDATION PIPELINE

For each RV-variable candidate we apply a multi-wavelength filter designed to select systems with strong gravitational evidence for a companion but little corresponding light. Key checks include Gaia astrometry/duplicity (including explicit neighbor searches), WISE/GALEX constraints, TESS/ZTF photometry, deep imaging, and X-ray/radio catalog searches.

5. CASE STUDY: GAIA DR3 3802130935635096832

5.1. DESI per-epoch RVs and extreme variability

The maximum catalog RV span is $\Delta\text{RV}_{\max} \approx 146 \text{ km s}^{-1}$ over 38.9 days. A constant-RV model is rejected at $\Delta\chi^2 \approx 2.7 \times 10^4$ (DESI-only). Two exposures on the same night are consistent in the catalog to within $\sim 1 \text{ km s}^{-1}$.

Table 4. DESI DR1 per-epoch catalog RV measurements for Gaia DR3 3802130935635096832.

Epoch	Source	MJD	Date (UT)	$\text{RV} \pm \sigma_{\text{RV}}$ (km s^{-1})
1	DESI	59568.488	2021-12-20	-86.39 ± 0.55
2	DESI	59605.380	2022-01-26	$+59.68 \pm 0.83$
3	DESI	59607.374	2022-01-28	$+26.43 \pm 1.06$
4	DESI	59607.389	2022-01-28	$+25.16 \pm 1.11$

5.2. Blend constraint from ΔG

The Gaia-resolved neighbor has $\Delta G \simeq 2.21$ mag. The corresponding G -band flux ratio is:

$$b_G = 10^{-0.4\Delta G}. \quad (5)$$

Table 5. Definitions for Equation (5).

Symbol	Meaning
b_G	Flux ratio in Gaia G (neighbor/primary; dimensionless)
ΔG	Gaia G magnitude difference (mag)
$10^{(\cdot)}$	Base-10 exponential
0.4	Magnitude-to-flux conversion factor

With $\Delta G \simeq 2.21$, $b_G \simeq 0.13$. Because the neighbor is close and likely redder, the effective flux ratio can be larger in the redder DESI Z arm than in G .

5.3. Per-exposure, per-camera forensic resolution of Z -arm instability

Motivated by earlier arm-split pathologies in coadds, we downloaded per-exposure DESI `cframe` products for EXPIDs 114768, 120194, 120449, and 120450 and measured RVs by wavelength region. We renormalize formal uncertainties by reduced chi-squared χ^2_ν and estimate RV uncertainties using a curvature-based $\Delta\chi^2 = 1$ criterion.

Same-night exposures (120449 and 120450; 15 minutes apart) show:

- Full Z arm yields a $\sim 34 \text{ km s}^{-1}$ discrepancy between exposures.
- Restricting to the CaII triplet window (8500–9000 Å) reduces the discrepancy to $\Delta\text{RV} \approx 2.8 \text{ km s}^{-1}$, i.e. a $\sim 12\times$ improvement relative to full- Z .

- Wavelength splitting within Z indicates that the sky-dominated 9000–9800 Å region is unstable, while the Ca II triplet region is stable between same-night exposures.

5.4. Trusted-window RV curve (Ca II triplet, 8500–9000 Å)

We define the Ca II triplet window (8500–9000 Å) as a trusted window for RV inference. Table 6 reports per-exposure RVs derived using only this window.

Table 6. Per-exposure RVs from the trusted window (Ca II triplet, 8500–9000 Å).

EXPID	MJD	Trusted RV	Catalog RV	Trusted – Catalog ²⁰⁹
114768	59568.488	−85.6	−86.39	+0.8 ²¹⁰
120194	59605.380	+65.6	+59.68	+5.9 ²¹¹
120449	59607.374	+53.1	+26.43	+26.7 ²¹²
120450	59607.389	+50.3	+25.16	+25.1 ²¹³

The trusted-window RV swing between the most extreme exposures is $\Delta\text{RV} \approx 151.2 \text{ km s}^{-1}$ (from -85.6 to $+65.6 \text{ km s}^{-1}$), consistent with the catalog-scale swing. Notably, the same-night pair is systematically higher in the trusted window than in the catalog by $\sim 25 \text{ km s}^{-1}$, consistent with the catalog solution being pulled by the unstable sky-dominated red end of the Z arm.

5.5. Same-night residual discrepancy and systematic floor

Although the trusted window dramatically improves stability, the same-night exposures differ by $\Delta\text{RV} \approx 2.8 \text{ km s}^{-1}$. The curvature-based uncertainties in the trusted-window fits are $\lesssim 0.4 \text{ km s}^{-1}$ per exposure, which implies formal high significance for this difference. However, the reduced chi-squared values in the trusted window remain $\chi^2_\nu > 1$ (typically 2–7), indicating residual template mismatch and/or remaining systematics. We therefore interpret the same-night residual as evidence for a few km s^{-1} systematic floor in windowed DESI RVs for this blended M-dwarf target, even in the trusted window.

6. PHOTOMETRIC, INFRARED/UV, X-RAY AND RADIO CONSTRAINTS

TESS photometry shows no deep eclipses or large coherent modulation. ZTF photometry places limits on large-amplitude rotational modulation, disfavoring

purely activity-driven explanations for a $\sim 150 \text{ km s}^{-1}$ swing. WISE colours ($W1 - W2 \simeq 0.05$) show no strong IR excess. GALEX NUV non-detection disfavors a hot WD companion. No significant X-ray or radio counterpart is found in major catalogs, consistent with a non-interacting (quiescent) system.

7. LIMITATIONS

The system remains unconfirmed due to:

1. Sparse DESI cadence (four epochs; two nearly simultaneous) and intrinsic period aliasing.
2. Confirmed close neighbor inside the fiber: blend-aware inference is mandatory.
3. Residual systematics at the few km s^{-1} level persist even in the trusted window.
4. LAMOST RVs are not decisive due to internal inconsistencies across extraction methods.
5. Gaia RUWE/AEN are elevated but are not uniquely attributable to orbital wobble given duplicity.

8. CONCLUSIONS

Gaia DR3 3802130935635096832 is an extreme DESI DR1 RV variable with a large catalog RV swing and a “darkness” profile (no strong IR/UV excess, no large photometric modulation, no cataloged X-ray/radio counterpart). Gaia DR3 confirms a close neighbor at $\rho \simeq 0.69''$, motivating blend-aware analysis. Per-exposure, per-camera validation identifies the sky-dominated red end of the Z arm as the source of previously observed instability; restricting to the Ca II triplet window yields a trusted-window RV curve with a $\sim 151 \text{ km s}^{-1}$ swing, consistent with the catalog swing, and explains why the catalog RVs for the same-night pair were biased low.

We therefore retain this system as a *strong but unconfirmed* dark compact companion candidate. The highest-value next step is high-resolution spectroscopy and/or high-angular-resolution imaging to separate the blended components and convert the large RV swing into a definitive dynamical mass constraint.

9. DATA AND CODE AVAILABILITY

All scripts, configuration files, diagnostic plots, and machine-readable results used in this work are publicly available at <https://github.com/simulationstation/DESI-BH-CANDIDATE-SEARCH>.

Software: DESI DR1, Gaia DR3, LAMOST, TESS, ZTF

Facilities: DESI, Gaia, LAMOST, TESS, ZTF